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Intelligent vector field visualization based on line integral convolution

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Abstract

In order to reflect the internal motion characteristics of entire vector fields, texture visualization methods based on line integral convolution are usually adopted. However, the visualization results obtained in this way have low image quality. To solve this problem, this paper suggests using line integral convolution to optimize two specific aspects - texture enhancement and color enhancement – to provide an enhanced vector field visualization model. Existing texture enhancement algorithms can create texture aliasing. Based on an analysis of the relationship between vector angles, sampling distance and texture aliasing, the paper puts forward a texture enhancement algorithm that uses the vector angle to adjust the sampling distance of a high-pass filter. This greatly reduces the presence of texture aliasing. For color enhancement, a linear algorithm is usually used that adds vector size information to the vector field. However, the resulting image has a problem of color concentration. In view of this, the distribution characteristics of the vector field are analyzed using a histogram and a dynamic nonlinear color enhancement algorithm is proposed. This noticeably improves the color distribution of the resulting image and improves the overall visual quality of the result.

Keywords: Vector field visualization; Line integral convolution; Texture enhancement; Color enhancement

1. Introduction

1.1. Background and significance

Vector field visualization technology is mainly used to display large-scale flow field data sets in scientific computing or to provide visual graphics for the purposes of simulation or human-computer interaction (Shi et al., 2018a). It enables researchers to intuitively and efficiently analyze complex changes in the flow field information present in datasets (Chang-Jun & Qiao, 2017; Zheng, Saxena, et al., 2018; Zheng, Sangaiah, et al., 2018). In recent years, scientists have proposed a variety of flow visualization methods, including direct visualization, geometric visualization, texture visualization, and feature visualization (Shi, Zhang, et al., 2017; Zheng, Huang, et al., 2016), with dense sampling being used to reflect movement characteristics and detail changes in the entire vector field. This avoids the need to select seed points (Yu-Jie, 2010). It is precise because of its overall scope that texture visualization is the chosen method for most researchers (Lin, Zhu, & Zheng, 2017; Shi, Zheng, et al., 2018; Sun et al., 2017; Tu et al., 2018; Zhou et al., 2018).

Texture visualization tends to focus on 3D vector field visualization, which is widely used in disciplines such as hydrodynamics, aerodynamics, and hemodynamics (Shi, Dou, et al., 2018; Sun et al., 2017; Wang & Pan,

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2014). When this method is applied to three-dimensional or higher-dimensional flow fields, problems such as texture occlusion, rough textures, aliased textures and low texture contrast often appear. This leads to poor visualization results (Lin, Wang, Wang, & Dou, 2016; Lin, Wang, Ma, et al., 2016; Song & Liu, 2016; Wu, Li, & Lin, 2016). A method for enhancing vector field visualization is therefore proposed here that can significantly reduce texture aliasing and enhance the contrast between streamlines (Dou et al., 2017; Li, 2013; Wang et al., 2017).

1.2. State-of-the-art

Texture visualization has its origins in the 1990s (Cabral, 1993; Liu, Guan, & Lin, 2017) and, so far, three approaches to texture visualization have been proposed; the point noise technique; the texture advection technique; and the line integral convolution technique. Line Integral Convolution (LIC) is the most important and commonly used of these techniques. It was first proposed by Cabral and Leedom in 1993 (Zhan, Hu, & Yuan, 2013). For each grid point in a vector field, a one-dimensional low-pass filter kernel function is used to convolve the noise texture so that it is bidirectionally symmetrical, thereby providing an output texture value. This method is able to characterize the motion of the whole flow field effectively.

Since the emergence of LIC, many researchers have sought to develop it, resulting in a number of improved algorithms. These improvements mainly concentrate on five aspects: algorithm execution performance; texture enhancement; hardware acceleration; stationary and unsteady flow fields; and applicability to different dimensional vector fields (Wang et al., 2014).

In 2013 Zhan and Hu improved the basic color mapping method (Lu, Zhu, Wang, Gao, & Ni, 2017). In order to highlight the vector field characteristics of a region of interest to users, a nonlinear color mapping method was used for the visualization. In 2014 Quan et al.. proposed a field-driven visualization method (Wang & Li, 2014) that improved the brightness of the texture and more clearly captured and displayed the features and regularities of the color gradient region of the vector field.

In 2017 a texture enhancement algorithm was proposed by Lu, Zhu, and Wang (2016). Here, the largest decrease in the pseudo-gradient of adjacent noise points was used to enhance the contrast between streamlines and adaptively adjust the noise weighting, according to local variations in the flow field, thus highlighting the vector texture details.

Texture visualization methods based on LIC can characterize whole flow fields more compactly and comprehensively than geometric visualization methods such as streamlines. They are also more sensitive than point noise methods (Cook, 1986). However, whilst they can clearly express the flow field details and vector direction (Lin, Wang, Wang, et al., 2016), they cannot express the flow field strength.

2. Optimization of texture enhancement algorithms using LIC

The original LIC algorithm resulted in an overall dark image, blurred lines, streamlines of low contrast, and poor particle mobility, which was not conducive to observing a vector field's motion characteristics. In order to enhance the contrast between streams, the LIC convolution texture needs to be enhanced. Inspection of the literature about texture enhancement and how to implement related flow algorithms reveals that the existing algorithms achieve texture enhancement by high-pass filtering the LIC convolution texture. However, this results in a serious texture aliasing phenomenon in the image. In order to solve this problem, we look closely here at how texture enhancement algorithms use high-pass filtering technology.

It turns out that the image texture aliasing phenomenon is caused by the way in which high-pass filtering uses isometric sampling, with the texture aliasing usually being related to the vector angles. By analyzing the relationship between vector angles, sampling distance and texture aliasing, it is possible to create a texture enhancement optimization algorithm that can use the vector angles to adjust the sampling distance. The workflow for this algorithm is as follows: First of all, vector field data and noise texture information with the same resolution are taken as input to perform an LIC texture convolution. After this, a certain proportion of the noise is injected into the convolution texture to enhance its randomness and the contrast between the streamlines. The convolution texture is then subjected to one-dimensional high-pass filtering texture enhancement. This uses a sampling distance that is adjusted by the vector angle and a designated filtering kernel function. Finally, the output texture is drawn and displayed using volume rendering technology. It is worth noting that, in order to enhance the contrast between streamlines in the output texture image, the preceding output texture is often used as the attribute texture for the next convolution. The basic framework of the algorithm is shown in Fig. 1.

2.1. The texture enhancement algorithm process

2.1.1. Texture convolution

Texture visualization of 3D stationary vector fields usually uses LIC algorithms, which take vector field data and noise texture information with the same resolution as input and use a one-dimensional low-pass convolution kernel function to make the entire noise texture bidirectionally symmetrical in the direction of the streamlines. This enables the output texture to show the spatial correlation of the streamlines. The calculation process for LIC (shown in Fig. 2) is as follows: for any pixel P in the vector field, using particle tracking technology in the positive and negative directions of the point vector with point P as its center, the streamline of the pixel point is obtained. The streamline is then used as an integral curve to check the noise texture values that correspond to all the sampling